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Solder Jet Printhead for Deposition of Molten Metal Drops[1]

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Abstract. *We have developed a drop-on-demand printhead that can eject molten metal droplets. The capability of ejecting solder drops onto an X-Y stage controlled substrate makes this new technology ideal for fast prototyping of metallic traces on planar and three-dimensional (3D) objects. The ejection process uses the electromagnetic repulsion force between two parallel currents moving in opposite directions. One current path flows through the molten metal, such as solder, the other through a copper stripe. The electrical connection between the two conductors was accomplished by two Ni plated vias. By adding an appropriate nozzle in the solder channel, a current pulse can cause a drop to squirt out. The size of the ejected solder drop depends on the driving energy, which is controlled by both the pulse width and the drive voltage. For successful operation of the printhead, wettability of the solder to the printhead material needs to be taken into consideration. We have constructed the solder jet printhead in both a polyimide laminate stack and a ceramic form that can withstand a much high temperature. We have ejected molten PbSn eutectic solder as well as BiSn and InSn with precision on Si wafers, over substrates with different heights and connecting the traces on different levels, as well as creating freestanding 3D structures. © 2010 Society for Imaging Science and Technology.*
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INTRODUCTION

As circuits progressively shrink, the requirement for interconnection has become increasingly more challenging. There are several approaches for solder bump formation, including evaporation,[1] electroplating,[2] paste stenciling,[3] and solder jetting. Solder jetting is ultimately the most attractive for its many advantages. It is a direct-write process requiring no shadow mask or transfer mask creation or alignment step. Solder jet simply uses the existing data file of the integrated circuit (IC) design and provides a quick turn process relative to all competing mask-using techniques. Compared to evaporation, where most of the solder is deposited on the mask, the cost and waste are minimized. The solder jet device is, in principle, compatible with all solder and alloy materials, allowing a wider range of materials use including high-temperature lead-free solders. The process is also flexible, allowing control of spatial variations in solder volumes on the particular substrate or circuit of interest. This lends itself well to custom packaging applications as well as solder-bump assembly repairs. The absence of masks uniquely qualifies solder jetting to the bumping repair process. In a digital fabrication of functional materials, the need to place metal trace at will without the need of a photolithography process makes it highly desirable. The noncontact printing process further makes it ideal for patterning conductive traces over nonplanar circuits.

There have been several approaches to fluxless soldering in microelectronic applications using drop-on-demand jetting. The small solder droplets have been formed by a piezoelectric transducer element,[4] magnetohydrodynamic force between a current flowing in between the poles of two permanent magnets,[5,6] or ultrasonic generator to create vibrations near a nozzle,[7] as shown in Figure 1. Piezoelectric ejection suffers from certain limitations. For sustained operation of the piezoelectric element, it is highly desirable to limit it to well below its Curie temperature; otherwise, its piezoelectric coefficients will degrade over time. The low pressure pulse of the printhead also makes it very prone to bubble trapping in the molten metal channels. Such bubbles further dampen the pressure wave and, in a severe case, block the transport of the molten metal through the channel. The smooth glass tube without any kinks and sharp corners, depicted in Fig. 1(d), is essential to ensure no bubble is trapped in its path. For high-speed industrial digital dispensing of molten metals, it would be desirable to have a printhead that contains multiple nozzles. It would be very difficult to construct a multinozzle piezoelectric array printhead to address this need. Analysis of the other cited technologies also shows major deficiencies.

The Commercial Print Engine Laboratory in Hewlett-Packard (HP) Laboratories has developed a drop-on-demand printhead that can eject molten metal droplets. The capability of ejecting solder drops onto an X-Y stage controlled substrates makes this new technology ideal for fast prototyping as well as novel bumping on three-dimensional (3D) objects. The self-align capability of solder reflowing process also makes it ideal for precision assembly of micromechanical components. This article describes the microfabrication technique used to manufacture the solder jet printhead and some of its characteristics. The same jetting technique can be applied to other 3D structures that require fluid channels as well as electrical connections, such as chemical sensors.

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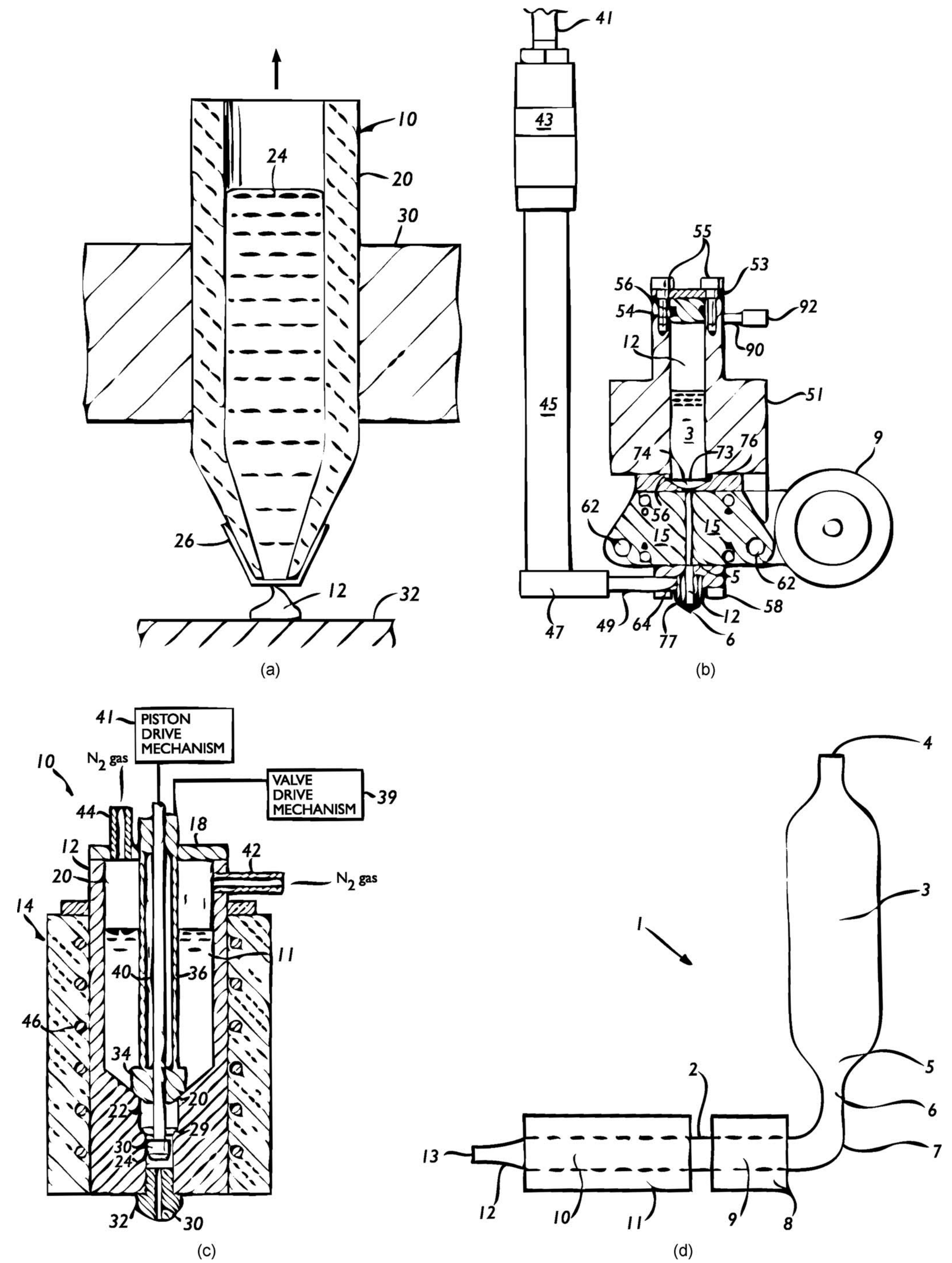


Figure 1. Metal drop ejection by (a) ultrasonic agitation, (b) current in a magnetic field, (c) mechanical piston, and (d) piezoelectric.

OPERATION PRINCIPLE

The ejection of the conducting droplets is accomplished by the mutual electromagnetic repulsion between two parallel conductors carrying opposing currents. In one implementation, as shown in Figure 2, one current path flows through the molten solder, the other through a copper stripe deeper in the printhead. The two conductors are separated by a dielectric layer, in this case a Kapton flexible circuit, and the electrical connection between the two conductors is accomplished by two Ni plated vias. The repulsive force between

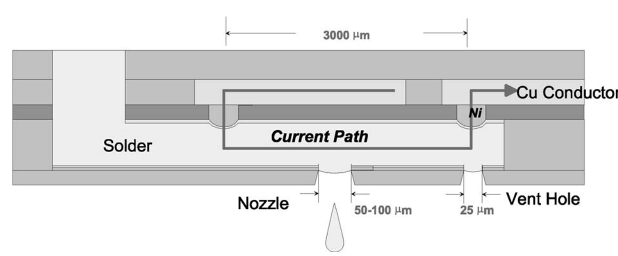


Figure 2. Operation of a metal jet printhead.

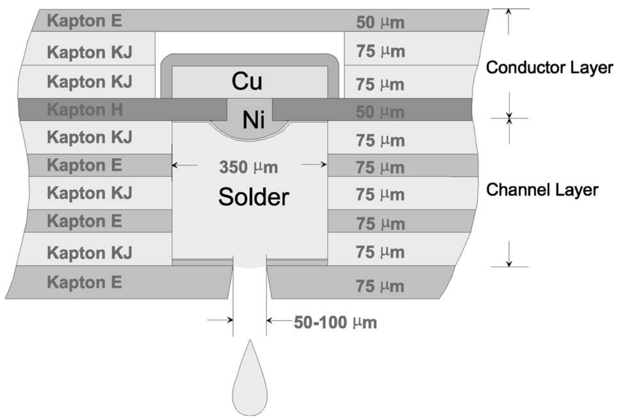


Figure 3. Cross-section view of metal jet laminates.

the two conductors with opposite current flow directions forces the liquid solder out of a nozzle located in the conduction path occupied by the molten metal, very similar to a thermal ink jet printing device.

The direction and magnitude of the repulsive force **F** are related to the cross product of an electric current vector **I** and a magnetic field vector **H** with $\mathbf{F}=\mathbf{I}\times\mathbf{H}$. For parallel conductors, the expulsion force can be estimated by a simple equation,

$$f=\mu_o I^2/2\pi D, \tag{1}$$

where f=force per unit conductor length and D=effective separation between molten metal and copper conductor. Here D is the dielectric thickness underneath the molten metal. For a given printhead, the amount of molten metal ejected through the nozzle increases with the current passing through the copper counter electrode and the molten metal.

Polyimide Printhead Fabrication

There are several possible configurations, as well as materials sets, for a solder jetting printhead device. One implementation is composed of polyimide laminates and a Cu flex circuit, as shown in Figure 3, in cross-sectional view. A cavity for solder channel is built on top of a flex circuit with copper traces on the back side and pairs of Ni plated vias on its front side. The solder channel is constructed by stacking up polyimide Kapton KJ/E layers. Each layer is micromachined by laser ablation with μm precision.

These layers of Kapton KJ/E and the Cu flex circuit are fused together by hot lamination using the bonding characteristic of Kapton KJ, a thermoplastic adhesive film with most of its physical properties comparable to other polyimide films. It has been shown to adhere to a variety of metallic and nonmetallic substrates. Bonding is typically done at 350°C and 3.4 MPa.

The height of the solder channel can be easily changed by varying the number of KJ/E layers, while the width of the channel can be changed by altering the software program for the laser ablation process. The size of the nozzle can also be changed by changing the aperture during laser ablation. This approach of polyimide/ablation allows us to quickly change dimensions of the solder jet printhead and greatly shortened the development cycles.

To ensure that the precise alignment between these layers is maintained during lamination, two alignment holes are precision drilled by laser ablation in each layer. Figure 4 shows an exploded view of each layer for a typical metal jet printhead. The left alignment holes are slightly undersized (~10 μm) for the alignment pin on the lamination fixture. The right alignment holes, on the other hand, are oversized in the x direction to accommodate for any possible machining errors in the lamination fixture.

The presence of a cavity on top of the flex requires the lamination be done in two steps. The bottom part is laminated first with the flex, two KJ, and one E layers. Cutout in the bottom KJ is designed to accommodate the thickness of the copper trace. After the bottom lamination, the top layers

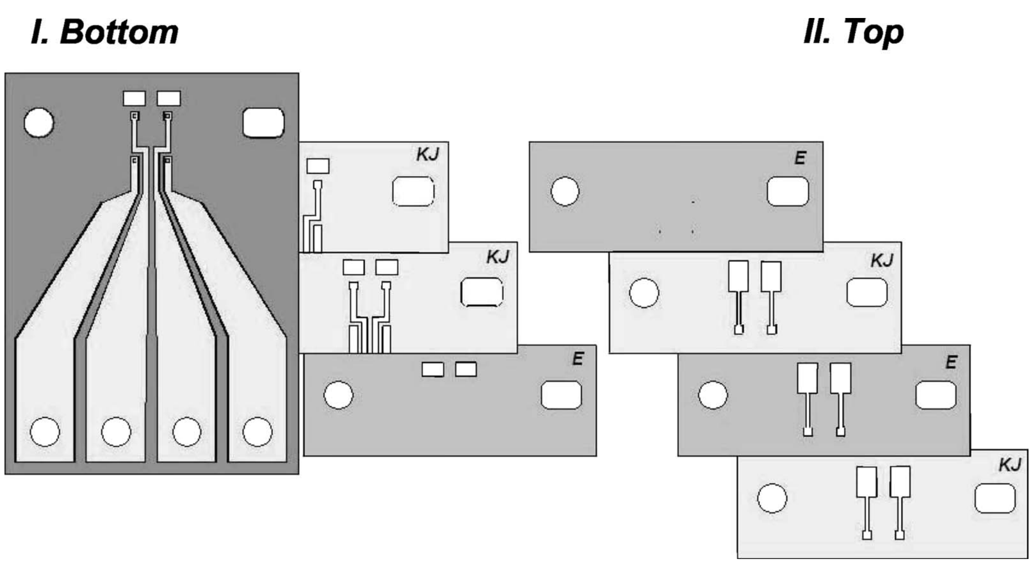


Figure 4. Exploded view of a metal jet printhead.

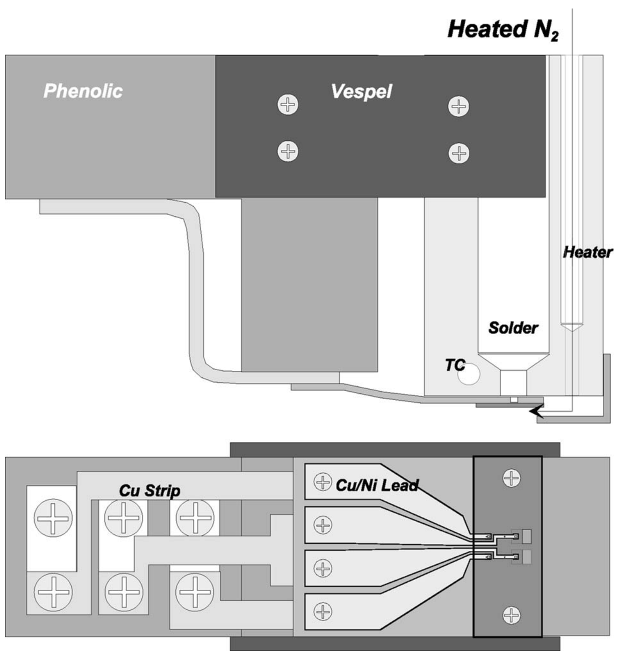


Figure 5. Pen body for metal jet printhead.

are fitted over the alignment pins for the second lamination. The top layers have a cutout for the solder channel. All the layers, except for the top nozzle plate, have two small rectangular holes for the solder to flow from the back of the printhead into the solder channel.

Metallurgical compatibility of the laminated polyimide has been tested by continuous immersion in a molten SnPb solder pot at 220°C. No sign of any material degradation or delamination was observed for well over 6 months.

The flex circuit printhead is mounted on an aluminum pen body, as shown in Figure 5. The backside of the solder jet printhead is attached to a solder reservoir. Solder is fed into the printhead by gravity. For successful operation of the printhead, wettability of the solder to the printhead material needs to be taken into consideration. Au and Ni thin films are sputtered deposited onto the polyimide components to assist the flow of solder in the solder channels during the initial priming of the printhead. As solder gradually fills the solder channel, the air inside is pushed out through the vent hole at the end of the solder channel. The location and the size of the vent holes are designed so that no solder will come out from the vent holes during operation.

No active back-pressure control is implemented in the printhead. Typically, in an ink jet printing device, such as a HP DeskJet™ print cartridge, a negative back-pressure is required to hold back the meniscus. Otherwise, the ink will drool out continuously from the nozzles. In the design of the solder jet printhead, the nozzle is shaped like an inverted funnel (Fig. 2), opposite to that of a typical thermal ink jet printhead. The meniscus stays at the bottom of the inverted funnel. During the ejection, the high surface tension of the molten solder pulls the extended meniscus back to the bottom, where the diameter is the smallest to minimize its surface energy.

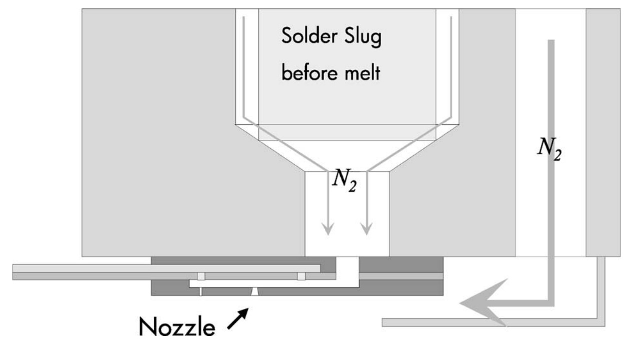


Figure 6. Nitrogen purging of nozzles and solder reservoir.

Solder oxides and impurities can clog the printhead if they enter the solder channel or form in the nozzle. To prevent this, three steps were taken in more recent implementations. First, the reservoir was filled with a solder slug, which was preformed in a flowing N_2 atmosphere. Second, passage ways were engineered inside the printhead so that both the solder reservoir and the nozzle area were constantly purged with flowing heated N_2, as shown in Figure 6. Third, the printhead assembly and the substrate were placed inside a box with flowing N_2 gas before the aluminum pen body was heated to melt the solder. Although the box was partially open to allow for microscopic observation of the jetting process, the flowing N_2 reduced the oxygen concentration sufficiently to prevent noticeable oxidation at the nozzle. With a sufficiently short working distance and the path bathed in N_2, the solder droplets did not oxidize significantly during flight before they solidify. The ejection operation was performed in a regular laboratory area without other special precautions for isolating the operation to prevent oxidation.

In the present implementation, there are two solder channels with one nozzle each in a printhead. It is possible to design more than two solder channels in a printhead. It is also possible to design multiple nozzles within one solder channel.

Ceramic Printhead for High Temperature Operations

A metal-jetting printhead with ceramic body construction would provide a large operating temperature range and thus greatly enlarge the choice of metals and alloy systems for ejection. We have employed multilayer ceramic (MLC) and glass sealing processing to build such a printhead. In the MLC fabrication, tape-cast ceramic blanks are shaped using die punching or laser machining. These blanks are typically printed with conductor pastes to form circuit traces and conductive vias. Various layers are then aligned in fixtures and laminated at pressures of 7–20 MPa and slightly elevated temperatures (60–80°C). During this process, organic components in the ceramic tape bind the blanks together forming an unfired or "green" body. A final firing results in organic burnout, densification, and formation of a monolithic three-dimensional structure. The ceramic printhead is completely ceramic; no metal traces are contained within the structure.

An exploded view of the ceramic head structure is shown in Figure 7. The main printhead body consists of four

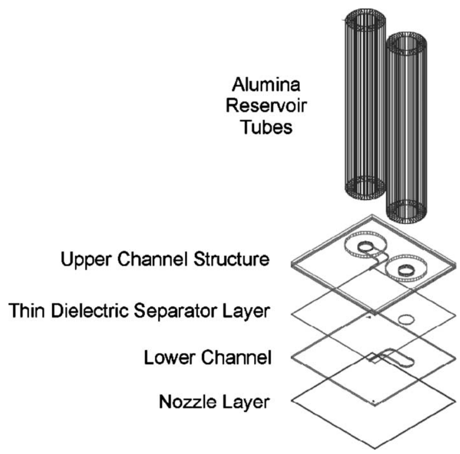


Figure 7. Exploded view of the ceramic head structure.

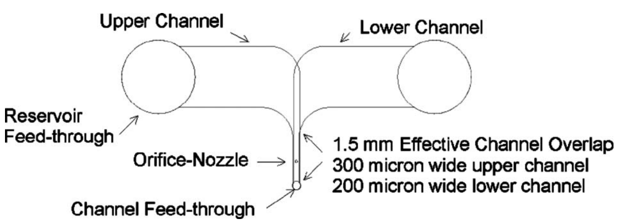


Figure 8. Overlapping solder channels in the ceramic design.

ceramic layers: the upper channel structure, a thin dielectric separator, the lower channel, and a nozzle layer. These individually fired layers, as well as alumina tubes, which serve as molten metal reservoirs, are glass sealed together to form the final printhead.

The thickness of the ceramic tape and the number of layers used determine the channels' height. The CO_2 laser machining profiles determine the channel widths. A top view of the overlapping channel profiles of one design is shown in Figure 8. The relative positions of the reservoir to channel feed-through, the channel interconnection feed-through, and the orifice are also seen. The two channels begin at the reservoir feed-through as 2.5-mm-wide openings that turn 90° as they narrow and overlap. The orifice is positioned in the center of the overlap region to ensure that the lower channel current in this region produces a uniform and repulsive magnetic flux. While smaller cross-sectional areas for the channels lead to a greater ejection force, the alignment tolerances during glass sealing set minimum values for the channel widths. The orifice diameter is typically $70-100$ μm. With alignment tolerances of ± 25 μm, we decided on a minimum lower channel of 200 μm and an upper channel of 300 μm. In the design shown in Fig. 8, the upper and lower channels fully overlap for 1.5 mm before terminating in a 325 μm diameter interconnecting via.

A high-temperature glass seal thick-film paste (ESL 4026A) with a thermal expansion coefficient chosen to match alumina was screen-printed on the upper and lower channel structures. A prefiring to 600°C was completed to remove organic components in the thick-film glass print. The four layers of fired ceramic, i.e., the upper channel structure, the thin dielectric separator, the lower channel, and the nozzle layer, were placed in an alumina fixture that allowed the layers to be referenced to two edges. A picture of the alumina fixture with the layers aligned is shown in Figure 9. The glass sealing of the layers was achieved by heating this assembly to 720°C. The glass thick-film paste was applied to one end of each reservoir tube and prefired as described above. These tubes were then place on the main body of the printhead, fitting into the alignment features of the upper channel structure. This assembly was again fired to 720°C to securely seal the alumina reservoirs to the embedded channel structure. The final assembly is shown in Figure 10.

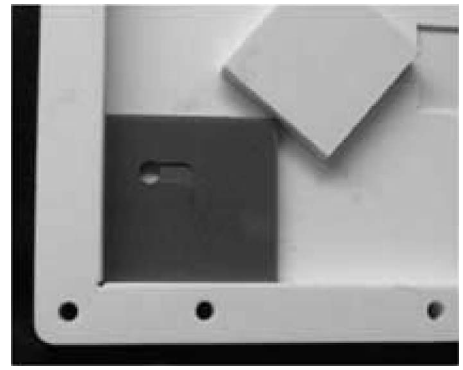


Figure 9. Alumina fixture with layers aligned.

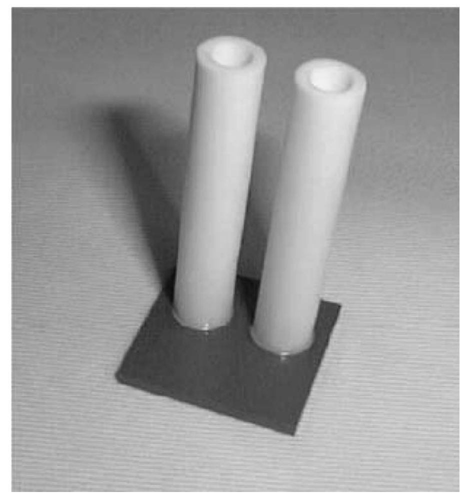


Figure 10. Final assembly of a ceramic head.

EXPERIMENTAL RESULTS

The solder jet printhead is driven by a custom pulse generator designed to inject a controlled current pulse through the solder jet head. The jetting process is current-based and hence benefits from a sharp well-defined input. The pulser is thus designed to quickly pump a significant current through the head by switching on charged capacitors and releasing short and high current pulses. The pulser is capable of delivering up to 800 A peak current at voltages up to 200 V. Figure 11 shows pulse shape with a 0.2 Ω series resistance, a typical value of the load resistance. The resistance from the solder jet head and the cable is <0.1 Ω.

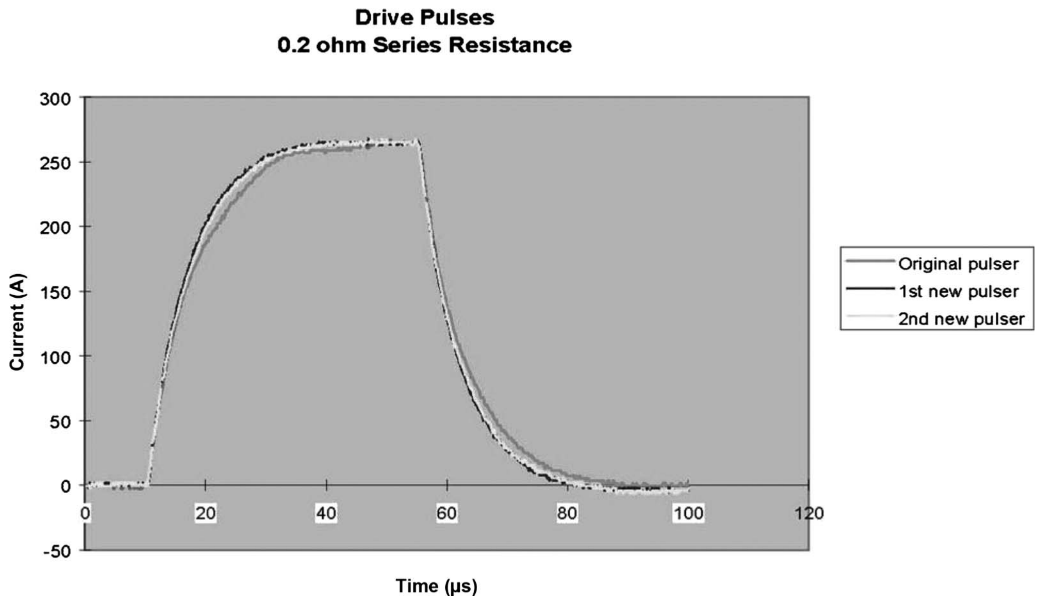


Figure 11. Pulse shapes from three different pulsers with a 0.2-Ω-load resistance.

Successful ejection of PbSn eutectic solder drops has been demonstrated. The size of the ejected drops depends on the driving energy, which was controlled by both the pulse width and the drive voltage, as shown in Figure 12. The size here is that observed on the Au/Ni coated Mylar sheet, on which a 5×5 pattern is deposited. The energy was estimated from the pulser current and the voltage to which the capacitor was charged. The wettable Au surface resulted in a flattened solder bumps with dimples in the middle of each bump. Some solder drops were also ejected into water, which produced spherical balls. A 200-μm-diameter solder bump on a Au/Ni coated Mylar sheet roughly corresponds to a 120-μm-diameter solder ball. Bump diameters increased with increasing applied voltages and pulse widths.

The energy delivered to the printhead varies with both the drive voltage and the pulse width. Figure 13 shows a summary of the dot size versus the total energy for all the experiments conducted on two printheads with different nozzle sizes: one 100 μm and the other 50 μm. For each printhead, all data points fall roughly in a continuous curve.

Typically, there is an optimal set of operating conditions for a given printhead. Energies above that range result in satellites, while underenergy droplets tend to have poor directionality. As expected, a smaller nozzle produced smaller solder drops. Perhaps contrary to intuition, a smaller nozzle requires a substantially higher energy than a large nozzle to eject solder. The turn-on energy of a 50 μm nozzle is almost double that of a 100 μm nozzle. The increase in drop size per unit energy for a smaller nozzle is also shallower than for a larger nozzle.

The solder drop ejection process was also examined by video camera with a strobe light source to look at the ejecting drops both at 30° and head-on (using a 45° mirror). Figure 14 indicates the arrangement of the video camera for the 30° observation. The photo to the left shows the solder meniscus pinned at the inner edge of the inverted nozzle plate. During pulsing, a solder column emerges from the nozzle. The break off of the column, the formation of a tail, and the merging of the tail to the main drop are all very similar to the aqueous analog emerging from an inkjet printhead. The much higher surface energy of the molten solder helps the tail merge with the main drop at an earlier

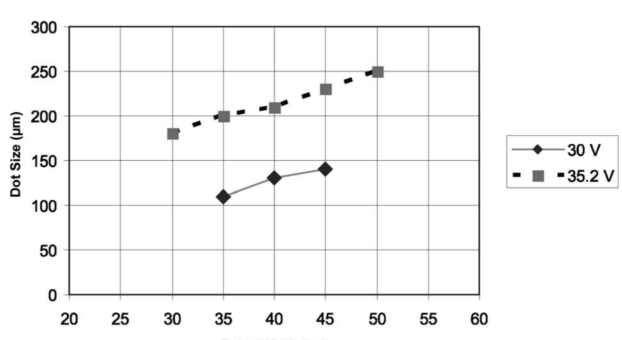


Figure 12. Effect of pulse width and voltage on drop size.

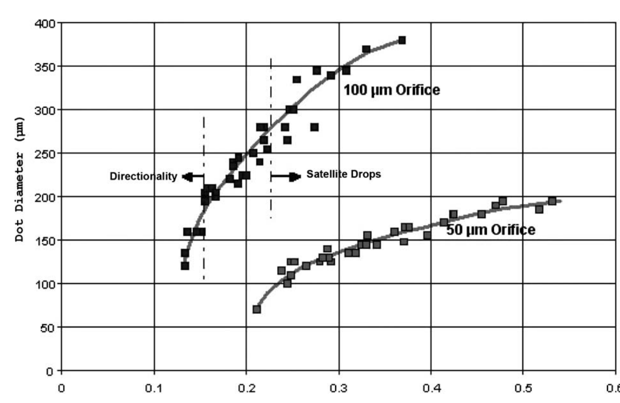


Figure 13. Effect of driving energy on drop sizes.

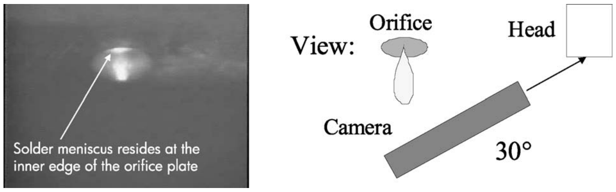


Figure 14. Video system for observing drop ejection. The meniscus can be seen at the very top of the nozzle. The bright region at the lower part of the nozzle is a reflection of the meniscus.

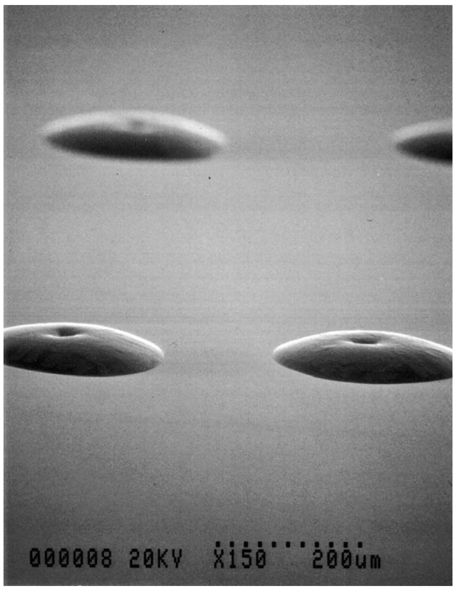


Figure 15. Solder dot deposited from a 100-μm-nozzle printhead.

stage than an aqueous drop, and the solder appears spherical soon after it emerges from the nozzle. The 3–5 m/s solder drop velocity is lower than that in a typical thermal ink jet printer, where it is closer to ~ 15 m/s.

At a standard working pen-to-substrate distance of 12 mm, the solder remains molten when it hits the substrate. Figure 15 shows a scanning electron micrograph of a solder dot array deposited from a printhead with 100 μm nozzles on a Mylar substrate coated with 100 nm Au. The excellent Au wettability results in a nice solder spread on the Mylar substrate. A separate modeling effort indicates that once the solder drop lands on the substrate, it oscillates a few times before finally solidifying within ~ 1 μs and leaving a characteristic dimple on its top surface. The dynamics of the oscillation and the actual solidification time depend on the substrate temperature. Most of our experiments were conducted with no substrate heating.

Figure 16 shows a portion of a 650×650 solder bump array deposited by a ceramic printhead. The bumps are 75 μm in diameter on 150 μm grid.

DISCISSION

Extremely stable operation has been observed in some cases. We have been able to pile up several hundred solder drops to form one single long straight column while printing at a working distance of 20 mm; the successive droplets just landed directly on top of the preceding ones, but significant directionality variations have been observed with other printheads. The lessons we learned so far indicate that we need to pay attention to priming and servicing the printhead for reliable operation. Keeping the solder oxide from appearing in the nozzle is also crucial. The placement accuracy can also be improved by reducing the working distance.

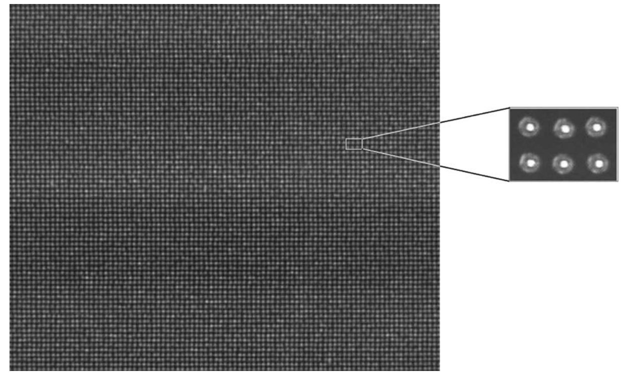


Figure 16. A portion of a 650×650 75 μm solder bump array deposited by the ceramic printhead.

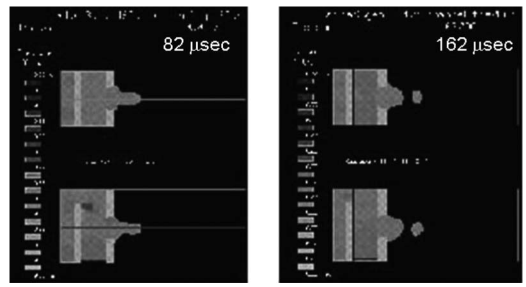
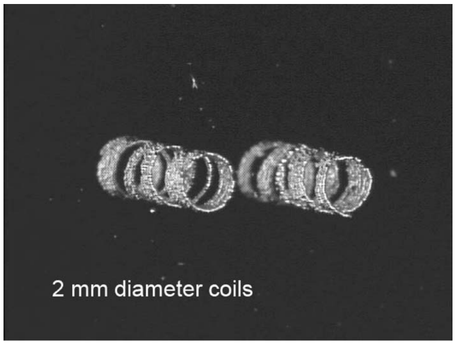


Figure 17. Finite-difference modeling of solder jet ejection.

A finite difference fluid model has been employed to characterize the architecture of the solder jet printhead, as well as strobe investigation of how solder drops formed. One major difference between solder jet and HP's highly successful thermal ink jet is the high surface tension of the eutectic PbSn solder. As the solder is being pushed out of the nozzle, the high surface tension affects how the solder column narrows down its tail, how the tail snaps, and how the satellite drops may form. Figure 17 shows one of the modeling results in two cross-sectional views.

The surface tension also dominates the energy required to push solder out of the nozzle. It is interesting to note that in thermal ink jet printing, a smaller nozzle requires smaller resistors to print. Less energy is needed to push aqueous ink out of smaller nozzle. On the other hand, Fig. 13 indicates that higher energy is required to push solder out of smaller nozzles. This can be attributed to the molten solder's high surface tension, typically around 542 dyn/cm, compared to water's 72.8 dyn/cm.

The high surface tension also dictates that the wetting characteristics of the printhead should be designed to facilitate the priming of the solder into solder channel. Without a wettable coating, or if the coating is contaminated, the molten solder would not be able to migrate down the solder channel in the printhead.



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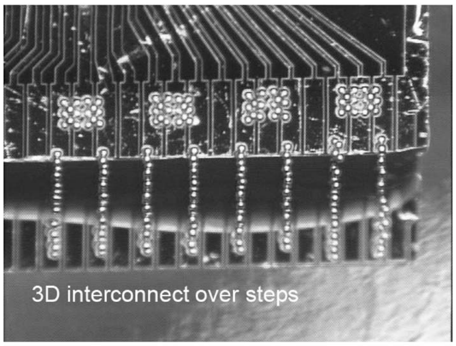

(b)

Figure 18. Examples of metal jet applications. The left image shows the metal coils as well as their fuzzier reflections from the substrate.

The polyimide printhead has a wetting layer designed in the sole channel for its easy filling of solder into the narrow channels. The easy refill also results in a higher refill rate, up to 120 Hz without external means to facilitate the flowing of molten solder in these channels, but eventually the wetting layer can delaminate from the polyimide substrate. If the firing remains at the same high frequency and molten solder cannot refill back into the upper electrode, the resultant air gap would cause arcing. On the other hand, the ceramic printhead uses an externally replaceable electrode without any wetting layer in its construction. Consequently, it is more difficult to prime the printhead and fill the channels with the molten solder. Yet because of its lack of a wetting layer, its operation is not limited by the delamination of the wetting layer. The ceramic printhead is also suitable for ejecting high melting point metallic drops other than solder bumps, such as copper or gold.

Figure 18 shows some of the examples of applications enabled by the stable operation of the solder jet printhead. The optical micrograph on top is a 3D ring with a 2 mm diameter. The ring was built up from successive solder drops landing on top of each other while moving the substrate table in a circular motion. The micrograph on the bottom shows the direct writing of conductive traces between bonding pads on two chips separated by a 350 μm step between two chips.

SUMMARY

We have successfully demonstrated a new ejecting apparatus using the principle of electromagnetic repulsion force between two parallel currents moving in opposite directions for ejecting solder bumps. We have implemented both a fast turn-around polyimide construction and a higher operating temperature ceramic construction. The drop sizes can be controlled by either the nozzle diameter or the driving energy for the printhead. The wide stable operation range enables digitally placing metallic bumps on either two-dimensional or 3D substrates. We have ejected molten PbSn eutectic solder, as well as BiSn and InSn, with precision on Si wafers, over substrates with different height and connecting the traces on different levels, as well as creating free standing 3D structures.

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